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ERTS-1 IMAGERY USE IN RECONNAISSANCE PROSPECTING

Evaluation of the commercial utility of ERTS-1 Imagery in structural reconnaissance for minerals and petroleum

D.F. Saunders, G. Thomas, and F.E. Kinsman
Texas Instruments Incorporated
P.O. Box 5621
Dallas, Texas 75222

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16. Abstract

Five areas in North America (North Slope, Alaska; Superior Province, Canada; Williston Basin, Montana; Colorado; and New Mexico—West Texas) are being studied for discernibility of geological evidence on ERTS-imagery. Evidence mapped is compared with known mineral/hydrocarbon accumulations to determine the value of the imagery in commercial exploration programs.

The general conclusion at this time is that there is a great advantage in photogeologic interpretation from the satellite viewpoint to provide a truly synoptic examination of regional geologic features. In addition to detecting lineaments which may be continental in scale, many large circular or curvilinear tonal or dissection patterns not generally detected on conventional aerial photos have been discovered. Preliminary analysis of these lineaments and curvilinear anomalies has established close empirical relationships between these features and both mineral deposits and the structure of sedimentary basins.

This report provides details of the Colorado Region interpretation.

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PREFACE

A. OBJECTIVE

The objective of this study is to evaluate, from the commercial viewpoint, the feasibility of using ERTS-I imagery as a medium for interpreting and mapping large-scale structural lineaments and other geomorphic features in Precambrian shield areas and basins containing younger sediments. The successful completion of this program could lead to new broad-scale applications of regional structural interpretations, utilizing ERTS-type imagery to provide improved guidance for reconaissance prospecting for minerals and petroleum.

B. SCOPE OF WORK

Five geographic areas (Figure 1) will be included in this study. Government-furnished ERTS prints will be studied in mosaic form to determine the relative utility of multispectral ERTS-I imagery as compared to aerial photography for lineament and geomorphic interpretations in mining and petroleum reconnaissance exploration applications. Seasonal and wavelength effects will be studied, and recommendations will be made for optimum applications of ERTS imagery for these purposes.

C. PRELIMINARY CONCLUSIONS

The general conclusion is that there is a great advantage in photogeologic interpretation from the satellite viewpoint to provide a truly synoptic examination of regional geologic features. Many large lineaments and other geomorphic features with dimensions of tens to hundreds of miles have been mapped. Many of the lineaments appear to be continental in scale in that they essentially extend continuously across the entire map areas shown in the index map. There are many large circular or curvilinear tonal or dissection pattern anomalies that outline caulderas, intrusive bodies, basins, etc. Many of these features have not been detected generally on conventional aerial photos or mosaics because of their close viewpoint.

Comparison studies show that smaller features such as fracture traces (lineaments less than 1 mile long) and lineaments up to 4 or 5 miles long are either not as detectable or not as easily discernible on the 1:1,000,000 scale ERTS imagery as they are on aerial photos. The use of 1:250,000 scale enlargements of ERTS scenes permits most of the smaller lineaments to be mapped, but aerial photos should be used for fracture trace studies.

The various MSS bands have been compared to determine the best ones for use; in general, it was found that the combined use of bands 5 (red) and 7 (infrared) as separate images will provide adequate information for most interpretations. The best single band and the best season of coverage depends on the problem to be solved and the region to be studied.

Experience to date with color composite images has been very limited. However, the simulated false color infrared composite of bands 4, 5, and 7 has been used and large tonal variations have been found because of processing differences between prints. This, combined with the necessity to use different seasonal coverages in mixtures to get cloud-free images, causes the final mosaic to be such a mix of tones that it is difficult to use. With constant tone processing,

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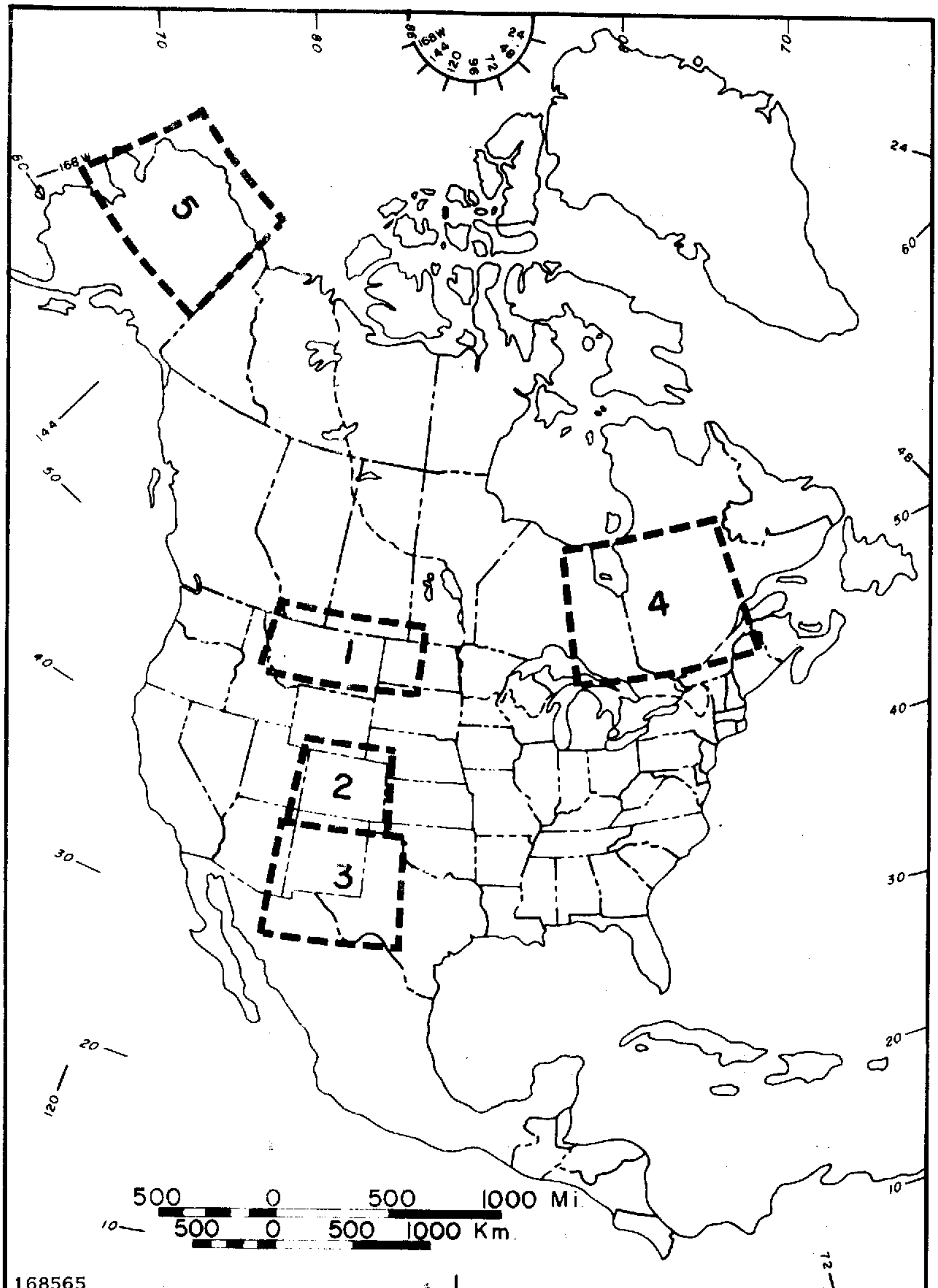

Figure 1. ERTS Study Areas, Investigation MMC-083

the color composites probably would be much superior to any single-band black and white prints for both lineament and tonal interpretation. Single-band black and white mosaics will be easier to use until more uniform tonal color products are available.

In interpretating lineaments and curvilinear tonal or dissection anomalies, close empirical relationships were found between these features and both mineral deposits and the structure of sedimentary basins. It is believed that this type of broad-scale geomorphology coupled with plate tectonic structural interpretations and regional geologic and geophysical studies can provide a radically improved approach to reconnaissance prospecting.

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SECTION I
INTRODUCTION

A. SCOPE AND PURPOSE

Technical progress during the 1 March 1973 to 31 August 1973 report period is covered in this report and plans for the remainder of the contract are summarized.

B. SUMMARY OF WORK

Satisfactory mosaics were completed for Area 1 (Montana region) and Area 2 (Colorado region). The preliminary mosaic for Area 3 (New Mexico region) was reworked to fill in coverage gaps and cloudy portions. Lineament and geomorphic maps were completed for all three areas at 1:1,000,000 scale. Similar scale overlays were prepared showing mineral deposits (gold, copper, lead, zinc and uranium), as well as oil and gas fields. Interpretation of the significance of the lineaments and geomorphic anomalies was completed for selected portions of both Areas 2 and 3.

Significant improvements were made in the mosaic coverage of Area 4 (Superior Province, Canada) and Area 5 (Northern Alaska), resulting in satisfactory coverage of each area so that interpretation can be performed. Information was gathered to prepare the necessary minerals and petroleum map overlays.

A study of seasonal variations and the relative utility of the four MSS bands in lineament and geomorphic interpretations was completed for all five areas.

SECTION II
TECHNICAL PROGRAM

A. STUDY OBJECTIVE

The general objective of the study is to evaluate the utility of ERTS-I imagery at 1:1,000,000 scale in commercial reconnaissance exploration for minerals and petroleum, and to begin to develop its role in helping to solve present and future resource problems. Specifically, this was to be accomplished by determining the feasibility of using ERTS-I imagery as a medium for interpreting and mapping large-scale structural lineaments as compared to using conventional aerial photos for this purpose. Other specific objectives included determining the optimum wavelength bands to be used and the best seasonal coverage to provide the necessary topographic, water feature, and tonal contrasts for lineament and geomorphic studies.

The eventual desired end product is the development of methods and approaches for future large-scale commercial utilization of ERTS imagery in mineral and petroleum reconnaissance.

B. BACKGROUND FOR THE INVESTIGATION

1. General

In recent years, increased attention has been given to considering continental-scale structural processes and their possible relationships to the formation of mineral and petroleum deposits. These include the new concepts of sea-floor spreading and plate tectonics as well as the older continental-drift theories. Details of interpretations and conclusions vary from one investigator to another, but one general theme seems to be emerging: the concept of a series of major zones of weakness in the continental basement rocks expressed as lineaments at the surface which have been sites of recurrent structural activity throughout much of geologic time. This recurrent activity along these weakness zones and the resultant stresses generated in the areas between the zones have produced folding and fracturing which can have a controlling effect on mineral and hydrocarbon deposit emplacement. A good understanding of the details of these relationships promises to offer a radically more effective reconnaissance prospecting tool.

For many years, "linears" or lineaments* detected visually or in geophysical data have been interpreted by geologists to represent the surface expression of buried faults or fracture zones. Hobbs in his description of the Atlantic border region was among the earlier writers to use the term "lineament" (Hobbs, 1911); however, the study of linear features and their geologic significance was pursued by John Phillips as early as 1828 (Umgrove, 1947). The methodology of mapping these features using aerial photography was described by Lattman (1958), and their use in geologic photointerpretation was summarized by Tator (1960). Until the advent of ERTS, it was not economically feasible to gather wide imagery coverage in the form of aerial photos in several wavelength bands at several seasons of the year, which is necessary for mapping these

*For the purposes of this study, linear or gently curved alignments of topographic features or tones identified on ERTS imagery are termed "linears," and those linears or groups of aligned linears which are interpreted to have geologic structural significance are termed "lineaments."

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linear features with optimum detectability. An additional disadvantage in using aerial photos has been the very large number of photographs necessary for continental-scale coverage. The work is very tedious, and the large number of edges between photos can be misleading or can obscure the surface lineament indications needed for mapping. ERTS imagery is providing a unique opportunity to obtain the necessary coverage and viewpoint to adequately evaluate this new prospecting approach.

Before ERTS-I was launched, studies of the geologic significance of imagery from satellite altitudes were pursued using Gemini and Apollo photography and degraded aerial photography. These experiments demonstrated the advantages of the satellite viewpoint in presenting synoptic coverage for regional tectonic studies and geologic mapping (Lowman and Tiedemann, 1971). It was suggested that the study of major wrench fault systems are especially susceptible to attack with orbital photography (Lowman, 1968; 1971). Studies utilizing aerial photography degraded to resolutions of about 100 meters illustrated the potential improvements in recognizing and characterizing very large features in ERTS imagery because of the loss or reduction of distracting details (Short and McLeod, 1972). Studies using Nimbus imagery showed that even with the very low resolution obtainable (2 to 5 nautical miles) regional geologic features could be discerned (Sabatini et al, 1971; Lathram, 1972).

2. Structural Reconnaissance for Minerals

a. Introduction

Many mineral deposits have been observed to occur along and adjacent to such prominent lineaments as the well-known Texas lineament of the southwestern United States (Wertz, 1970). Stokes (1968) noted the genetic relationship of most ore deposits in Utah with relatively obscure, generally northeast-trending fractures that cut diagonally across the presently outlined mountain blocks. The deposits also are concentrated along well-recognized belts which trend in a generally easterly or northeasterly direction. Landwehr (1967, 1968) observed that with few exceptions, the centers of intrusion which produce minerals in the western United States lie in seven northeasterly-trending belts which he interprets to reflect early Precambrian zones of crustal weakness. Crockett and Mason (1968) describe the use of "megastructural" elements in the "basement complex" and unmetamorphosed "cover" rocks as essential guides in future exploration for diamonds and nickel in South Africa. They consider these to be zones of crustal weakness related to major lineaments which have served as foci of mantle disturbances over long periods of geologic time.

The details of the relationship of deposits to lineaments or belts have remained somewhat obscure, and prospecting applications have been limited mostly to searching along these trends. However, a new interpretive technique was developed recently (Thomas, 1971), and was based on observations published by Sales (1968). This new interpretive concept and the new general theories of plate tectonics (Dewey and Bird, 1970; Isacks, Oliver, and Sykes, 1968) and continental drift (Morgan, 1968; LePichon, 1968; Carey, 1958) seem to offer a promising means of applying lineaments to fuel and mineral resource exploration.

This new concept is based on lateral movement on lineaments during orogenic stress, thereby coupling the interlineament continental plates or blocks by simple shear-producing deformational features which include folding and faulting.

Before publication of Sales' simple shear concept, the prevailing lateral fault theory was based on pure shear mechanics as conceived by Moody and Hill (1956). Figure 2 shows the difference between pure shear and simple shear. In pure shear, the compressional force is in line; that is, the incoming compressional force is directly opposed by a buttress effect. Resulting fold axes are perpendicular to the primary force direction, which is the bisectrix of the shear fractures shown on the strain ellipsoid. In simple shear conditions, the strain model is deformed by secondary compressional forces generated within the plate or block by the rotational action of the couple. Resulting fold axes occur at regular characteristic angular relationships to the bounding lineaments.

Moody and Hill postulated in their wrench-fault theory that basement zones of weakness are produced as master shear fractures during pure shear Precambrian orogenies. Subsequent orogenic stress reactivated these master shears laterally to form dragfolds and faults which, in turn, gave rise (when laterally reactivated) to still higher orders of dragfolds and faults. Eight orders of dragfolds and faults were postulated. Today, the many orders of Moody and Hill wrench-fault tectonics above the first and second order are being questioned. With the publication of Sales' simple shear mechanics, pure shear mechanics long considered as the basic mountain-building process is now being reexamined.

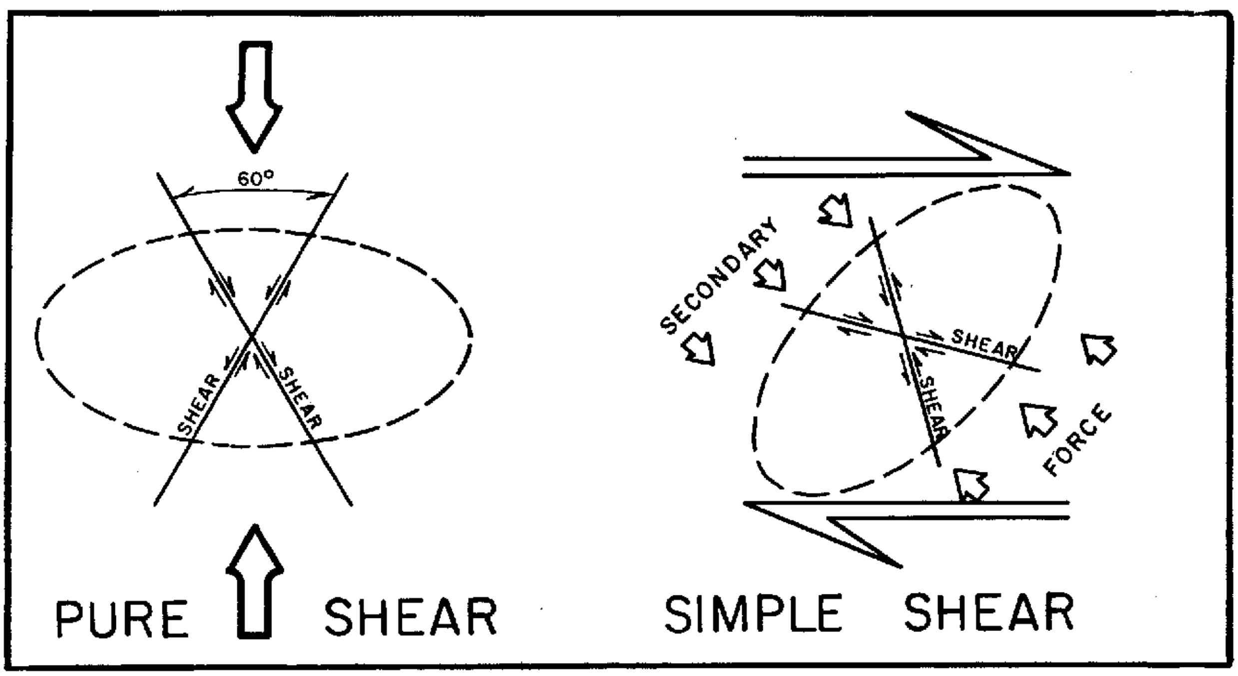

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Figure 2. Comparison Between Pure Shear (In-Line Compression) and Simple Shear (Differential Horizontal Movement)

b. ***Simple Shear-Plate Coupling***

The various degrees of lineament simple shear-plate coupling are briefly examined and some recognition characteristics for simple shear tectonics are pointed out in the following paragraphs.

Figure 3 illustrates three general stages of plate coupling as a function of increased simple shear on the plate-bounding lineaments which causes rotation of the couple-generated uplifts, faults, and fractures. The three general stages (incipient, moderate, and advanced) are used more for the convenience of discussion than for any precise classification. This is because couple deformational results occur as continuous responses to stress intensity. It is common to recognize advanced coupling near the plate-bounding lineament (Figure 6) and incipient to moderate coupling in the plate proper.

As is evident from Figure 3, the dragfold uplift generated by coupling is characterized as being confined between the major lineaments along which the simple shear adjustment took place. Flank faults, step faults, and cross-fold tensional fractures or faults are also confined between the lineaments. Conjugate shearing is generally of secondary importance. During greater coupling intensity, previously formed flank or cross-fold faults can become local shear zones.

A fourth coupling stage (extreme coupling) is recognized in zones where simple shear reaches a maximum. As shown in Figure 4, the characteristic *en echelon* dragfolds of advanced coupling begin to override one another during extreme coupling, thrusting out the intervening syncline or Z-fold connection.

c. ***Applications in Minerals Reconnaissance***

In minerals reconnaissance, the problem is to delineate those tension zones that can act as mineral conduits or depositional sites. The trends and general locations of these zones can be defined, utilizing the premises of the simple shear-plate couple theory (Thomas, 1971) and the locations of the known major lineaments. For example, Figure 5 shows a preliminary map of the major lineaments on the Superior Plate of the Canadian Shield, along with the "greenstone belts" and inferred tension zones. The sites of commercial mineral localities are shown by triangles. The major lineaments are indicated at the surface by abrupt structural-trend changes or by major lithologic changes such as those occuring along the Grenville Front lineament or the Thompson-Cape Smith lineament. Lineament control of the deposits is suggested by the proximity of some of the deposits to major lineaments (especially Grenville Front) and by the fact that the favorable host rock "greenstone belts" occur in trends that intersect the major lineaments at angles ranging from 35 to 45 degrees. This angular range of intersections suggests coupling in the areas between the major lineaments, since right-lateral incipient coupling would (as illustrated by the strain ellipsoid diagrams, Figure 5) produce similar fracture trends as tensional features. Such mechanics may very well have produced Precambrian horsts and grabens in the Superior Plate, or block, at 35- to 45-degree angles to the major lineaments. Deposition in the grabens, subsequent orogenesis, and metamorphism of and mineral emplacement in the graben sediments followed by long periods of erosion could explain the geologic picture seen today: Highly mineralized greenstone belts, crossing ancient granite terrain in remarkably consistent trends, all of which terminate at major northeast lineaments. Using this kind of analysis to find tensional zones could guide prospectors to general areas with good possibilities for undiscovered deposits.

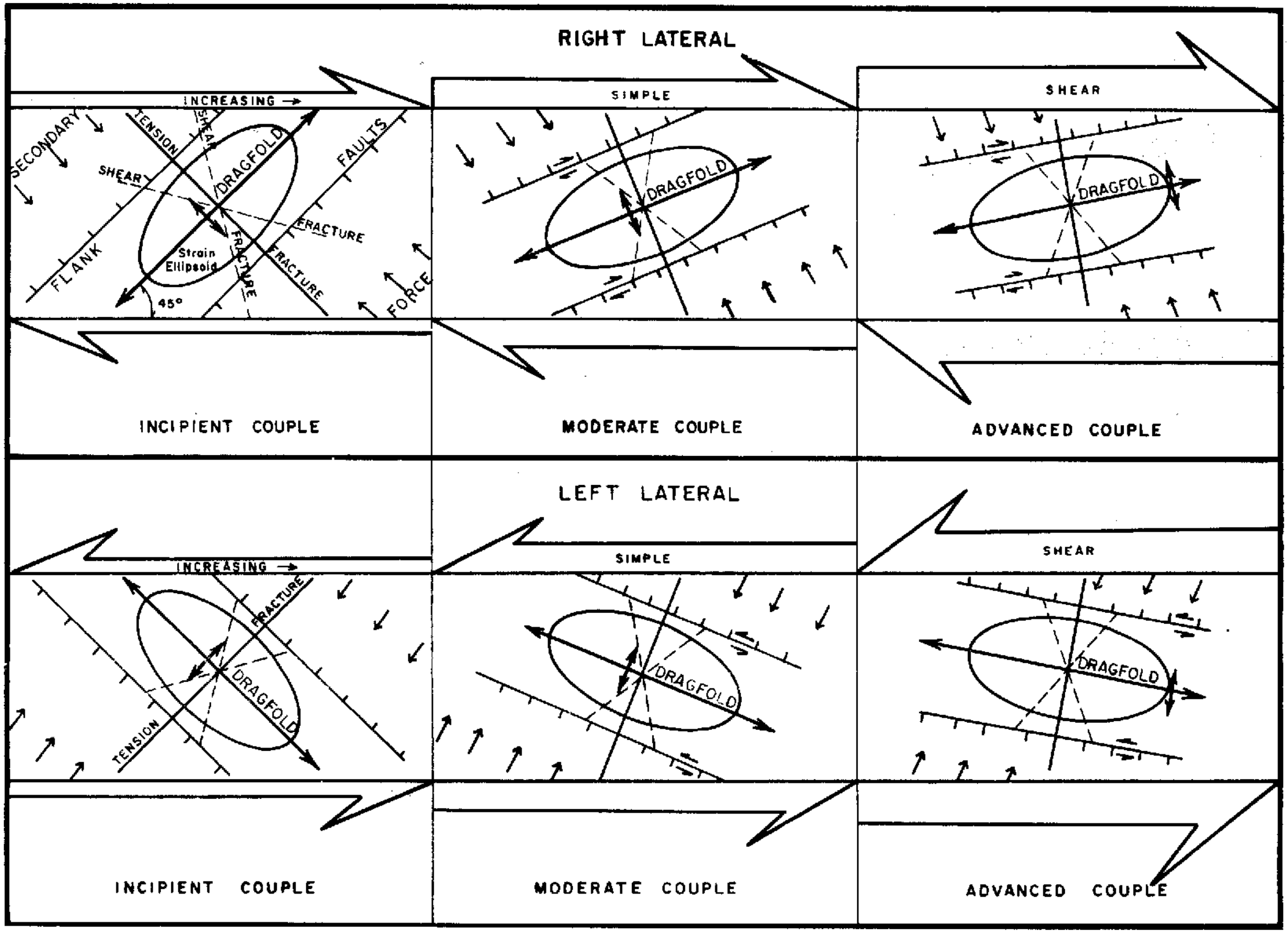

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Figure 3. Simple Shear-Plate Mechanics

3. Structural Reconnaissance for Petroleum

a. *Introduction*

The same general approach in structural analysis (using a series of basement plates subjected to coupling by simple shearing along basement weakness zones) can be applied in analyzing and predicting potential oil structures in the sedimentary basins.

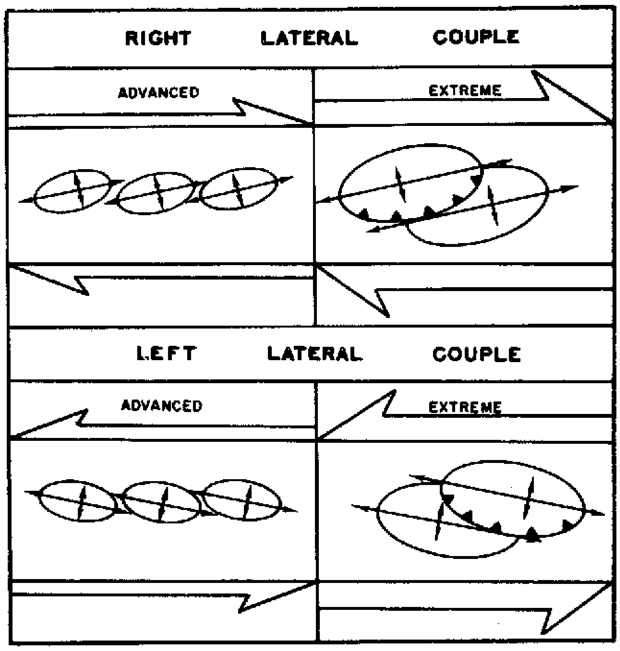

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Figure 4. Simple Shear-Plate Couple (Advanced to Extreme Stages)

b. *Applications in Petroleum Structural Reconnaissance*

Basement weakness zones which pass beneath sedimentary basins are generally represented at the surface as linears or lineaments in the form of:

- Tonal alignments brought about by vegetation or moisture conditions unique to the lineament zone
- Physiographic alignments produced by erosion
- Straight stream courses, also a product of erosion.

All of these criteria for lineaments generally depend on one common condition: increased rock fracturing in the sedimentary rock (Lattman and Matzke, 1961) above the basement weakness zone because of lateral reactivation of the basement feature in response to orogenic stress. By itself, increased rock fracturing along linears and lineaments in a sedimentary basin can have a pronounced effect on rock porosity and permeability, and on the ultimate recovery of hydrocarbons.

Another means of applying lineament mapping and subsequent structural analysis in a sedimentary basin involves recognizing the effects of simple shear in sedimentary rocks above a basement weakness zone. Figure 4 shows the characteristic *en echelon* arrangement of dragfolds that can be expected to be produced in the sedimentary section if the basement weakness zone has adjusted laterally to an advanced stage of simple-shear coupling. The Piceance basin of western Colorado and the Williston-Blood Creek basin of eastern Montana display such structural effects (Figure 6). Both sets of anticlines (Figures 6A and 6B) are marked by their *en echelon* arrangement. Each succeeding fold occurs slightly offset to the southwest, similar to the effects in the left-lateral advanced coupling diagram of Figure 6. Quite often, folds of this type which cross sedimentary basins contain hydrocarbons, and are primary target localities in a basin-wide search for hydrocarbons. Since the basement weakness zone which is the cause of the folding is generally represented as a surface lineament on aerial photographs or ERTS imagery, basin lineament mapping is a first step in defining more favorable zones for hydrocarbon accumulation.

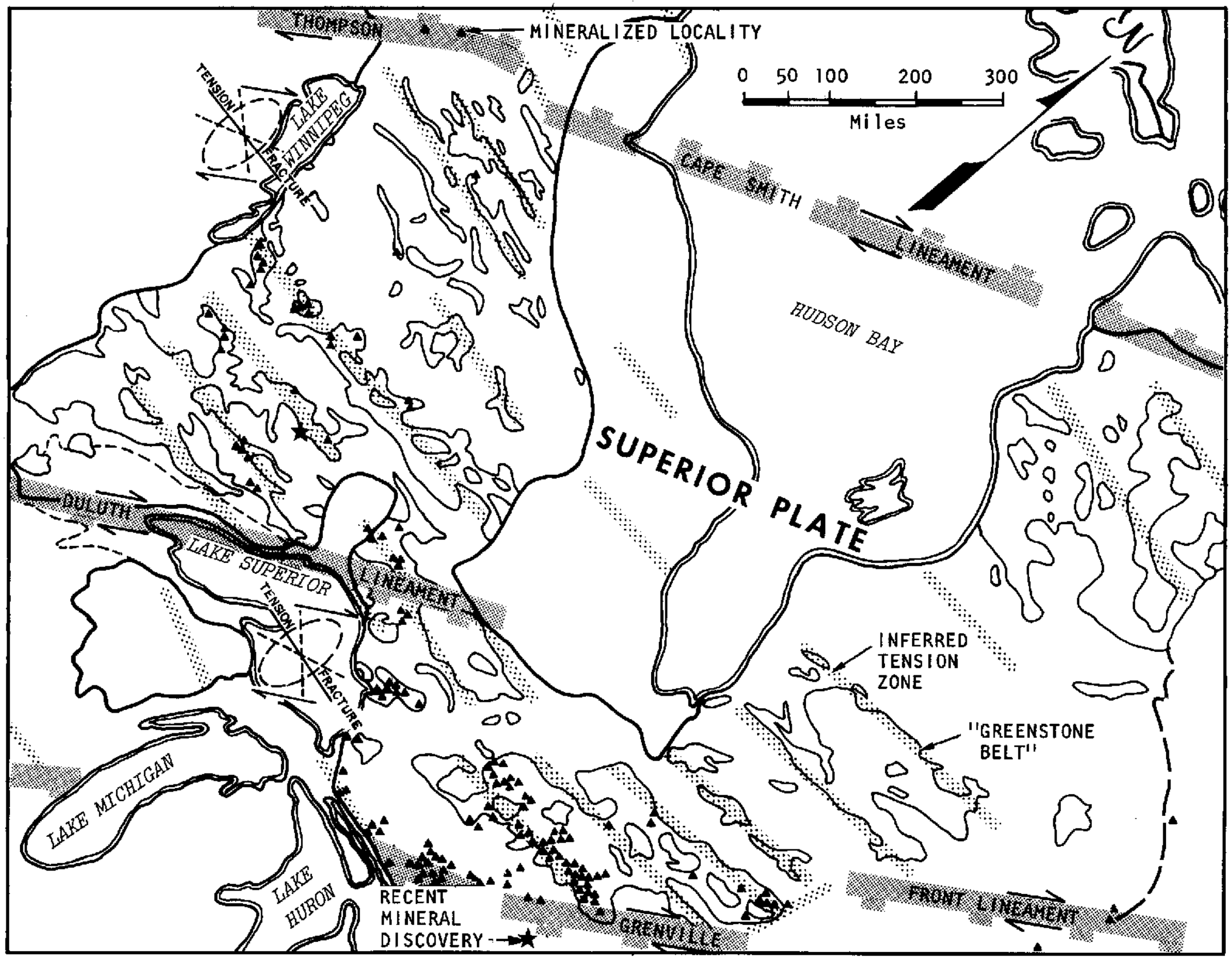

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Figure 5. Major Lineaments and Tensional Zones in Superior Plate

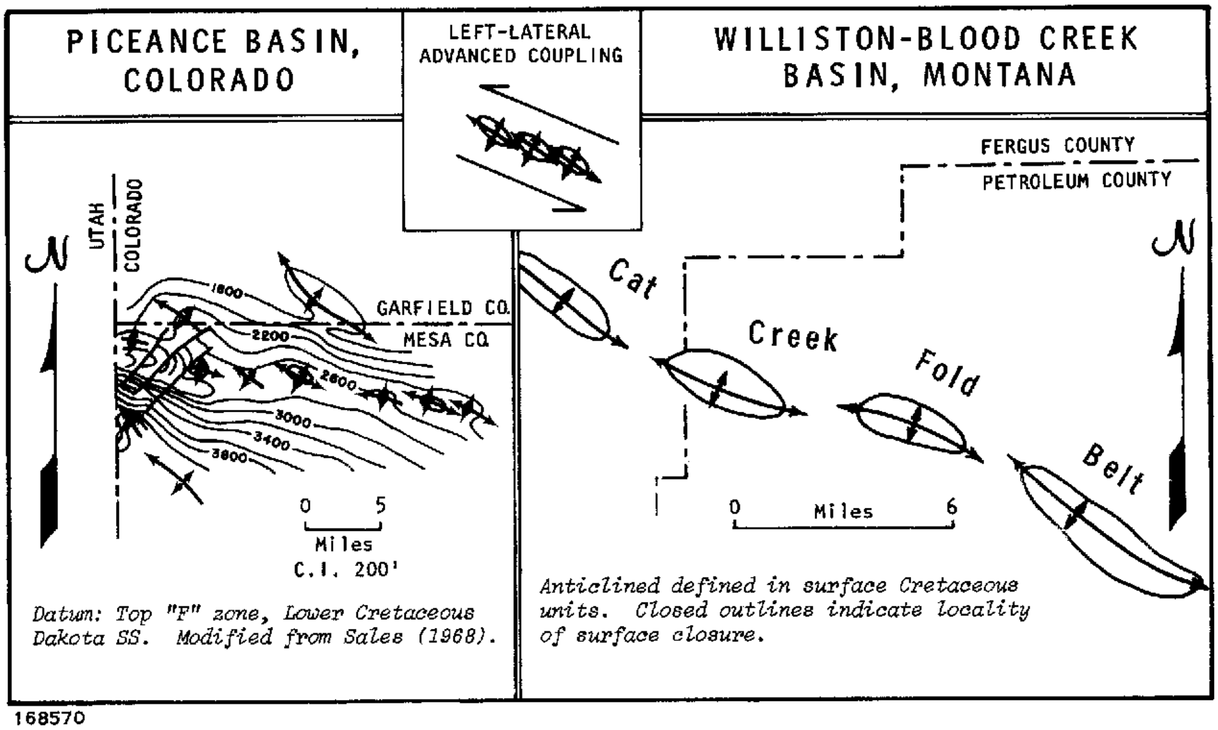

Figure 6. Basement Weakness Zone; Left Lateral Adjustment Effects in Strategraphic Basin

Besides using lineaments and subsequent structural analyses of the lineaments to define localities of increased fracturing and structural dragfolds in sedimentary basins, it has been recognized (Sikabonyi and Rodgers, 1959) that lineaments, being reflections of basement weakness zones, may have affected paleotopography and thereby may have influenced paleodepositional conditions. Since most hydrocarbon accumulations require proper lithologic conditions, it is of the utmost importance in the search for hydrocarbons to be able to define zones or localities of changing lithologic conditions. Sikabonyi and Rodgers (1959) pointed out the marked parallelism of Paleozoic lithologic changes with faults expressed as surface lineaments in northeastern British Columbia and northwestern Alberta. Thomas (1971) showed similar parallelism and truncation of Paleozoic and Mesozoic units with surface lineaments in southwest Wyoming. In both cases, the annotation of lineaments in the respective areas, combined with a structural analysis to define paleostructure and topography, should provide a promising means of defining paleodepositional conditions, an essential step in the successful search for hydrocarbons.

In some instances, the direct mapping of lineaments may very well define zones of exceptional shelf development and resultant depositional features as illustrated in Figure 7. Here, a massive reef limestone facies that may contain hydrocarbon reserves has grown in the stratigraphic section above a basement weakness zone. If the zone is represented at the surface as a lineament, lineament mapping may be a direct means of defining a reef trend. In other instances, a structural analysis of the lineament data may be necessary to define those areas where vertical changes in the paleotopography would be more likely, thereby providing control for ancient shelf development. In either case, the mapping of the lineaments would be helpful in the initial reconnaissance of sedimentary basin for petroleum prospecting sites.

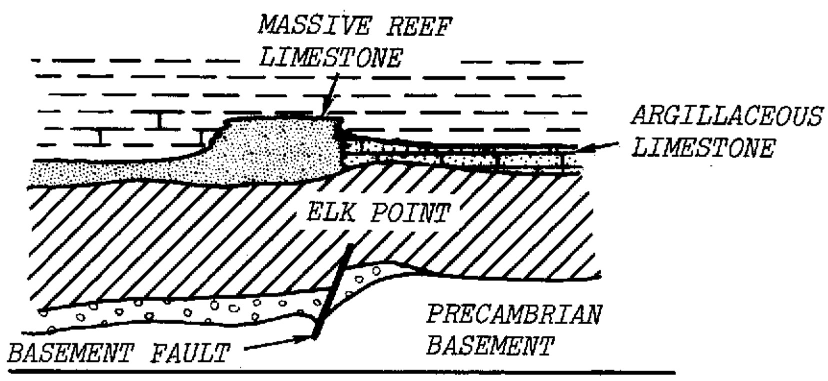

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Figure 7. Growth of Reef Over Basement Weakness Zone

C. STUDY AREAS AND METHODS

1. General

The five study areas (See Figure 1) were chosen to provide a representative variety of types of geology, physiography, and climates which included portions already mapped by Texas Instruments personnel so that conclusions could be drawn in comparing ERTS imagery with aerial photography as lineament mapping media.

Originally, it was intended to prepare seasonal mosaics for each test area in each of the available spectral bands. Experience soon demonstrated that only partial coverage could be obtained for each season because of areas of persistent cloud cover. It was found to be more practical to evaluate variations in interpretability due to seasonal changes and different spectral bands by comparing individual images of representative scenes within the "master" mosaic of each area. The master mosaics were constructed from the best quality MSS band 6 (red band) images available regardless of the collection season. Band 6 was chosen as the best single band for lineament interpretation. The choice was based on comparisons of the preliminary mosaics of separate bands and on general experience in comparing large quantities of individual prints. This choice is supported by studies of multispectral photographic images which simulate ERTS observations where the contrasts of geologic features were optimized in the red band (Short and MacLeod, 1972).

It was originally planned to select small regions within each area for comparing lineaments with known mineral or petroleum deposits and with previous mapping based on aerial photos. Preliminary inspections and interpretations of the mosaics showed that the most significant advantage of ERTS imagery was in mapping very large scale lineaments which were not discernible on aerial photos. This was because of their large size as compared to the limited area coverage of individual photos. The decision was made to interpret the entire coverage of each area in terms of known mineral and petroleum deposits to better demonstrate the regional extent and significance of many of the lineament zones.

2. Mosaics and Lineament Mapping

The 9- by 9-inch positive prints of band 6 were mosaicked for each area, using the best and most cloud-free images available. As each shipment was received from NASA, the prints were inspected and compared with the mosaics to ensure that optimum coverage was obtained. The microfilm and Cumulative Standard Catalogs of ERTS images were inspected to try to find coverage for all gaps and cloud-covered areas. Where possible, these were filled by reordering.

When complete, each mosaic was photocopied to produce 1:1,000,000-scale prints for interpretation. The linears in each area were mapped separately and independently by three experienced interpreters who used transparent overlays and colored drafting tapes. The three linear maps were then superimposed and a final map was constructed using heavy dashed tapes for those linears agreed upon by the three interpreters, medium tape for those mapped by any two interpreters, and light dashed tape for those mapped by only one interpreter. This procedure was adopted to maximize objectivity in picking out these sometimes very subtle features. Anomalies indicated by curvilinear tonal and dissection patterns were then mapped by the principal and coinvestigator.

Aligned patterns of linears were then sought which appeared to have regional structural significance and these "lineaments" or "lineament zones" were connected by Zip-a-Tone patterns. Names were assigned to the most prominent ones and to those recognized as being previously reported in the literature.

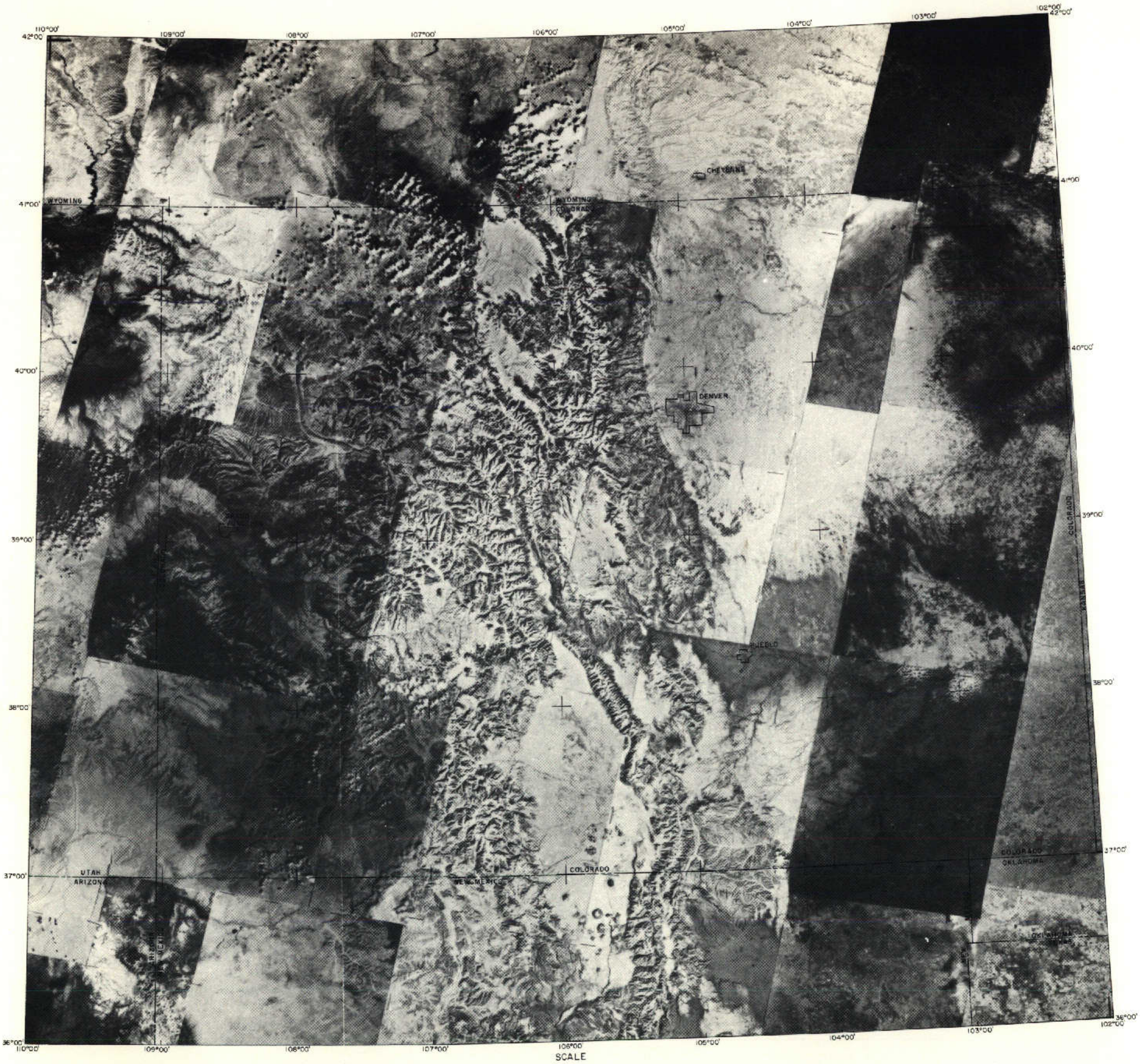
Transparent overlays were prepared showing the mineral localities and oil or gas fields at the same scale. Data on gold and base metal deposits in the conterminous United States were obtained from Kinkle and Peterson (1962), McKnight, et al. [1962 (a) and (b)], and Koschmann and Bergendahl (1962). Uranium data for that area were obtained from Finch, et al. (1959), and Schnabel (1955). Oil and gas locations were taken from Vlissides and Quirin (1963). These and all available geologic and tectonic maps at scales between 1:500,000 and 1:5,000,000 were used to evaluate the significance of the lineaments and geomorphic anomalies. The detailed structures associated with selected major mineral occurences were studied to determine their relationships to the regional structural patterns.

D. AREA 2 INTERPRETATION (COLORADO REGION)

1. General Observations

Figure 8 shows the master mosaic prepared for Area 2. The images are the best available in band 6 as selected for regional lineament interpretation, regardless of season of coverage. The image observation identification numbers are given in Figure 9.

ERTS AREA 2 COLORADO BAND 6



SCALE

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TEXAS INSTRUMENTS

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Figure 8. Area 2 (Colorado Region) Mesaic

ERTS AREA 2 COLORADO BAND 6

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Figure 9. Area 2 (Colorado Region) Observation Identification Index

Many of the more subtle linears cannot be easily discerned on Figure 8 because of degradation in the reduction and reproduction process, although they were easily visible on the original mosaic. However, an example of a strong linear can be seen trending southwest from Denver. This has been named the INDEPENDENCE PASS–NORTH FORK lineament because it is closely coincident with strong Precambrian shear zones reported in those areas (Tweto and Sims, 1963, Plate I, localities 6 and 4). This and all other linear features of the mosaic were mapped and graded as described in Section C. The resulting linears are shown in Figure 10 as an overprint on the mosaic.

The strongest features, those which show regional trends and those which represent previously reported lineaments, were named, and the strongest and/or longest are accented by shading in Figure 11. An attempt was made to retain the recognized names of the previously reported features. New features were named after recognized topographic features, where possible.

The well-known WICHITA lineament zone is outlined roughly by the heavy dashed lines. It appears to be interrupted by the LA VETA zone and its westward extension may trend along the WET MOUNTAINS, LEADVILLE–UINTA–UINTA MOUNTAINS lineaments and associated linear segments. Another possible alternative is that it is *en echelon* with the GUNNISON, PARADOX, UTE and HENRY lineament swarm. Based on the combined interpretation of Areas 2 and 3 (New Mexico Region), it appears more likely that there is another major lineament zone consisting of the PARADOX, UTE and HENRY lineaments trending southeast and joining to form the LAMESA lineament in West Texas. This would tend to strengthen the possibility that the WICHITA joins the WET MOUNTAINS, LEADVILLE–UINTA MOUNTAINS trend which could conceivably join with the LAMESA–PARADOX, UTE, HENRY lineaments west of the mapped area. Schmitt (1966) implied this possibility in his map of the major structure and ore deposits of the western Cordillera and his description of the Uinta–Wet Mountain–Wichita structural zone and the Salt Valley–Las Vegas (New Mexico) zone. The latter is coincident with the PARADOX, UTE, HENRY–LAMESA lineaments as mapped from the ERTS imagery.

The major named lineaments are described in Table 1 with the directions of their trends. In cases where more than two trends are evident because of lineament curvature or branching, both are given. An inspection of Figure 11 shows that there are several apparent series of parallel to subparallel lineaments. These were divided into trend ranges (Figure 12) along with the relative number of lineaments in each range. The major trends are seen to be northeast and northwest, with minor series trending east to west, north-northwest and east-northeast.

The strong northeast "grain" which crosses the generally north-northwest trend of the mountain ranges may be explained in terms of tensional fracturing which would be produced by large-plate simple-shear left-lateral coupling between the major west-northwest trending lineament zones such as the WICHITA, PARADOX–LAMESA, TEXAS, and so forth. Such tensional features exert stronger control on the direction of stream channels than would normal faults or shear zones, and therefore would tend to emphasize the lineaments defined by them.

The strongly favored northeast lineament trend is similar to the predominant direction of strike of mineralized veins in Colorado (Landwehr, 1967) and to the hypothesized Precambrian structural "grain" thought by many to be a controlling influence on the Precambrian and the younger ore deposits in the Western U.S. (Landwehr, 1967, 1968; Schmitt, 1966; Stokes, 1968; and others). The visibility of these Precambrian weakness zones through the younger covering

ERTS AREA 2 COLORADO BAND 6

Figure 10. Area 2 (Colorado Region) Linear and Curvilinear Anomolies

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ERTS AREA 2 COLORADO BAND 6

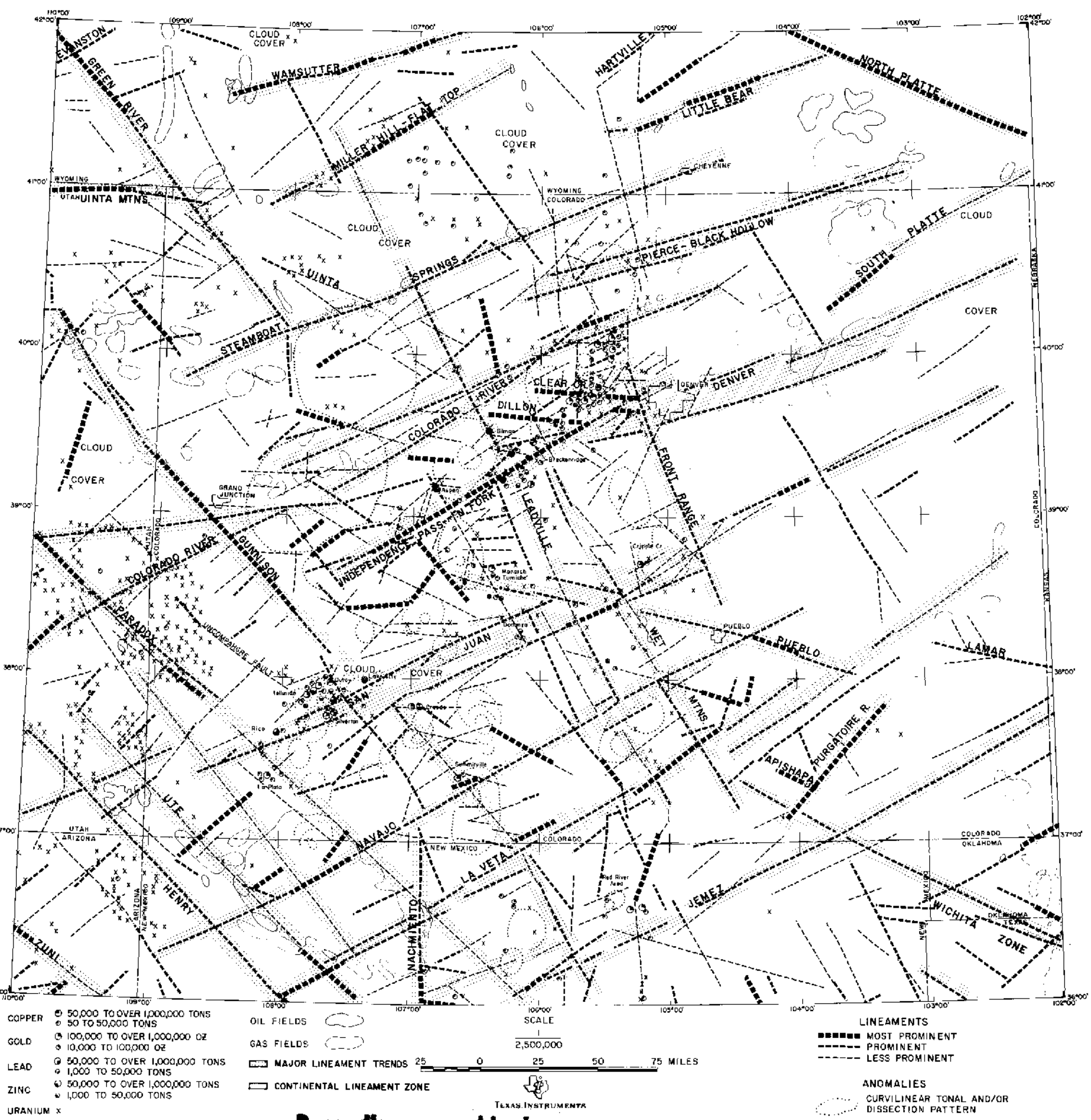

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Figure 11. Area 2 (Colorado Region) Data Interpretation

TABLE 1. AREA 2 (COLORADO REGION) MAJOR LINEAMENTS

Name	Trend(s)	Remarks
Evanston	N 56 E	Tonal alignment
Wamsutter	N 73 E	Linear stream courses
Hartville	N 51 E	Linear stream courses (Stone, 1968)
Miller Hill–Flat Top	N 58 E	Tonal alignments–linear stream courses (Stone, 1968)
Little Bear	N 70 E	Linear stream courses
Steamboat Springs	N 65 E	Tonal alignments–linear stream courses
Pierce–Black Hollow	N 73 E	Tonal alignments (Stone, 1968)
South Platte	N 50 E N 55 E	Linear stream course
Colorado River	N 59 E	Tonal alignments–linear stream courses
Denver	N 70 E N 80 E	Tonal alignments
Independence Pass–North Fork	N 58 E	Linear stream courses–tonal alignments (Tweto and Sims, 1963)
San Juan	N 64 E	Linear stream courses–tonal alignments
Navajo	N 58 E N 64 E	Linear stream courses–tonal alignments
La Veta	N 54 E N 61 E	Linear stream courses
Jemez	N 63 E	Deflected stream course–tonal alignment (Mayo, 1958)
Green River	N 139 E (N 41 W)	Linear stream course, physiographic alignment
Uinta Mountains	N 87 E N 97 E (N 83 W)	Physiographic alignment
Uinta	N 107 E (N 73 W)	Tonal alignment, linear stream course (Stone, 1968)
North Platte	N 114 E N 66 W	Linear stream course
Gunnison River	N 135 E (N 45 W) N 145 E (N 35 W)	Linear stream course, deflected stream
Leadville	N 152 E (N 28 W)	Physiographic alignment (Mayo, 1958; Central Colorado Belt lineament)
Front Range	N 160 E (N 20 W)	Physiographic alignment (Mayo, 1958; Laramie lineament)
Paradox	N 130 E (N 50 W) N 140 E (N 40 W)	Linear stream courses
Pueblo	N 102 E (N 78 W)	Linear stream course
Lamar	N 102 E (N 78 W)	Linear stream course
Ute	N 133 E (N 47 W)	Tonal alignment (Kelley, 1955)
Henry	N 133 E (N 47 W)	Tonal and physiographic alignments (Kelley, 1955)
Apishapa	N 119 E (N 61 W)	Linear stream course (Stone, 1968)
Nacimento	N 179 E (N 1 W)	Physiographic alignment fault zone (near Mayo's 1958 Cordilleran Front Belt lineament)
Wichita Zone	N 115 E (N 65 W) N 126 E (N 54 W)	Tonal and stream course alignments (Sales, 1968; Schmitt, 1966)
Purgatoire River	N 42 E	Linear stream course
Clear Creek	N 94 E (N 86 W)	Linear stream course
Dillon	N 93 E (N 87 W)	Linear stream courses
Wet Mountains	N 150 E (N 30 W)	Physiographic alignment and linear stream courses

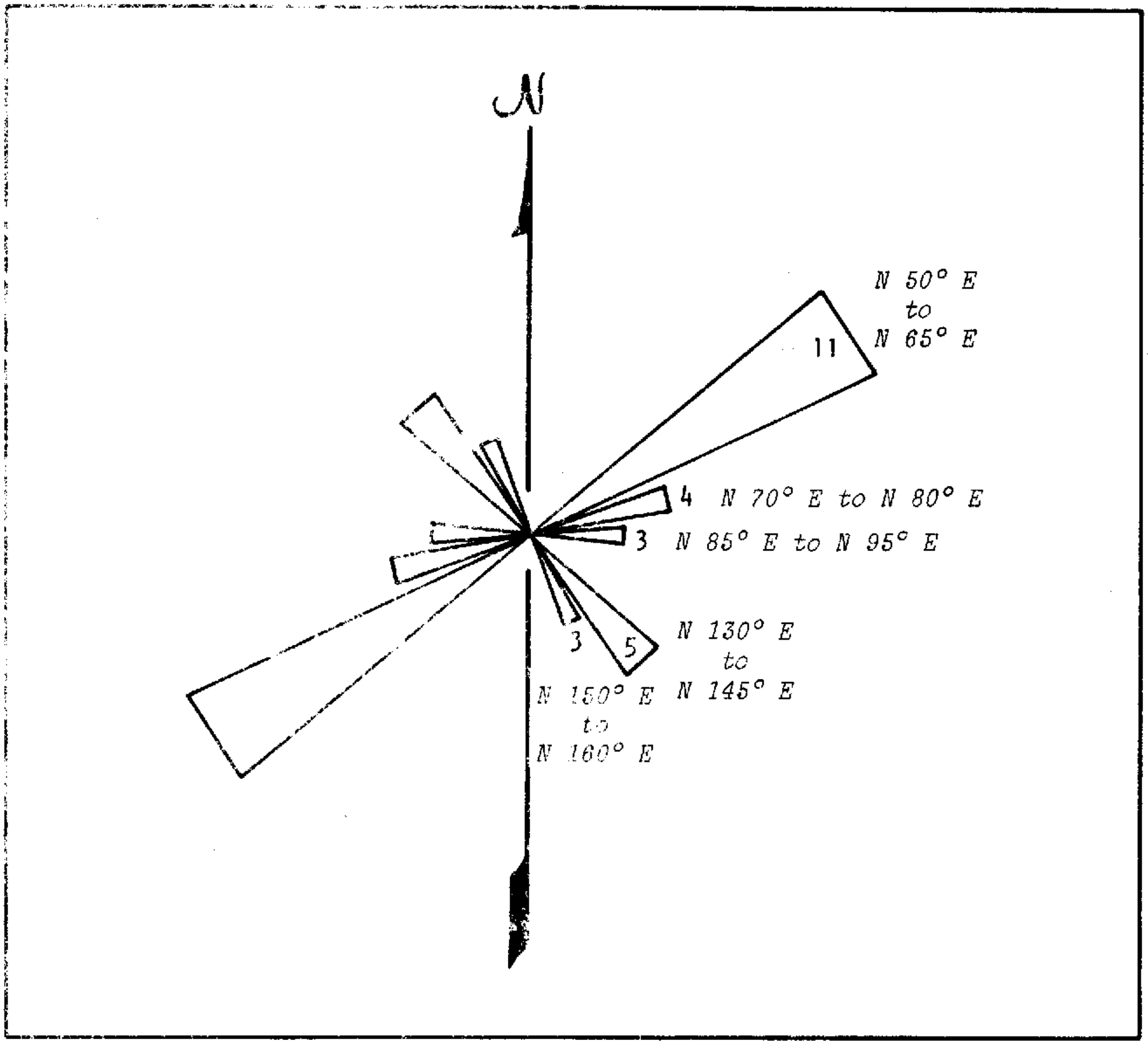

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Figure 12. Area 2 (Colorado Region) Lineament Trends

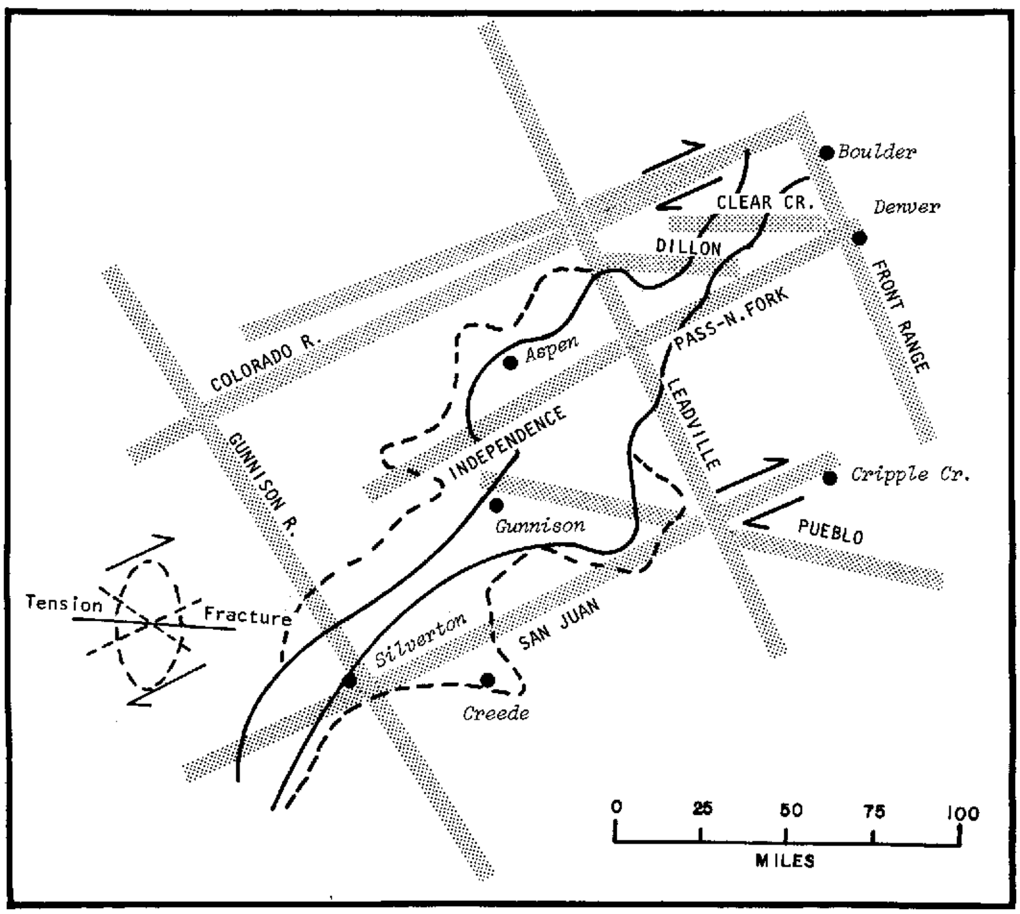
rocks is explained as being caused by recurring adjustments along the zones which control the jointing and faulting directions in the overlying rocks (Hodgson, 1965). These, in turn, control the tonal and erosional patterns visible on ERTS imagery. Thus, for the first time there is visible evidence of the strong northeast trending "grain." This may very well be the key to a much better understanding of the structural history of our major mining and petroleum producing districts.

In addition to the lineament interpretation of the mosaics, prominent circular or curvilinear tonal anomalies and dissection patterns were mapped and are illustrated in Figure 11. These features appear to represent structures such as intrusive bodies, cauldera, uplifts, basins, etc. Their significance will be discussed in the following subsection.

2. Correlation of ERTS Data with Economic Deposits

a. Precious and Base Metals

The majority of the major precious and base metal deposits of Colorado are distributed along the long-recognized Colorado mineral belt (Tweto and Sims, 1963) shown in Figure 13. Tweto and Sims showed that the belt follows an ancient zone of weakness defined by northeast trending shear zones of Precambrian age. They expressed the opinion that these zones not only localized the mineral belt but played an active part in its origin. To test the hypothesis that ancient and deep-seated zones of crustal weakness can be expressed as linears or lineaments in the ERTS imagery, a detailed comparison of Tweto and Sims' map of the Precambrian shear zones was made with the linear features shown in Figure 11. Their Idaho Springs-Ralson shear



Mineral belt boundaries as defined by principal mining districts of Laramide age

Maximum boundaries as defined by all intrusive porphyry bodies and mineralized areas of Laramide age, and mining districts of Tertiary age in the San Juan Mtns.
(After Tweto and Sims, 1963)

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Figure 13. Major Lineaments and the Colorado Mineral Belt

zone is coincident with the northeast trending linear crossing just east of the center of the CLEAR CREEK lineament. Shear zones near Berthoud Pass are seen as the northeast trending linear crossing the western portion of the CLEAR CREEK lineament. Tweto and Sims' North Fork fault and Independence Pass shear zone fall directly on the Texas Instruments INDEPENDENCE PASS–NORTH FORK lineament as noted previously. Tweto and Sims' zone of northeast lineations in the River Portal Schist of the Black Canyon of the Gunnison is right on strike with that lineament just beyond its southwest end, as mapped. Tweto and Sims' Homestake shear zone shows two major strike directions, northeast and east-northeast, which intersect south of Oilman, Colorado. Both of these appear as lineaments on Figure 11. This high degree of coincidence provides strong support for using ERTS imagery in extending and connecting local shear patterns to provide a regional interpretation of the mineralization control by Precambrian crustal weakness zones.

From the regional viewpoint, the Colorado mineral belt is bounded on the north by the COLORADO RIVER lineament zone and on the south by the SAN JUAN lineament zone as indicated in Figure 13. In the central and northern part of the belt, many of the mineral deposits mapped in Figure 11 appear to be associated with (or on strike with) east–west lineaments such as the CLEAR CREEK, DILLON, PUEBLO and many small linears of similar strike. If it is hypothesized that right-lateral simple-shear coupling on the plates included between the major northeast lineaments, the cross-fold tensional fracturing would strike essentially east to west as shown by the strain ellipsoid in Figure 13.

Left-lateral coupling on the continental lineament zones trending west-northwest leads to generally east-northeast trending tensional features. Such tensional features should provide good channelways for mineralizing solutions. An inspection of Figure 11 shows a close association of the major mineral occurrences with either northeast or east–west trending lineaments. Predominant northeast-to-east by west strikes of mineralized veins in Colorado (Landwehr, 1967) were discussed earlier. Thus, the ERTS data, the field observations and the plate tectonics/simple shear theory all seem to agree that the east–west and northeast directions are preferred for mineralized structures in this region. This indicates that linears and lineaments with these general strike directions should be the most productive for prospecting.

Figure 11 also shows the curvilinear tonal or dissection pattern anomalies as dotted lines. As a general observation, the precious and base metal mines of Colorado tend to be located around the edges of these features, particularly where a linear crosses the curvilinear anomaly. This relationship is particularly striking in the San Juan Mountains where many studies have illustrated the localization of most known ore deposits around the youngest subsidence cauldera in the complex (Stevens, 1968). These cauldera or "cauldrons" are nearly circular features and comprise part of a large area of complexly overlapping volcanic subsidence structures of the middle Tertiary age. Stevens reports that exploration for concealed ore deposits in the Creede Mining District have already been successfully guided by the relationship of the known deposits to the edges of the youngest cauldera, and that this approach should be helpful in judging the potential of other areas nearby. He states that although several of these cauldera are known, undoubtedly many others remain undetected.

Figure 14 shows the relationship of the ERTS-mapped cauldera which appear as circular dissection anomalies with the major ore deposits in the Western San Juan Mountains. The well-known Silverton and Lake City cauldera (Burbank and Luedke, 1968) are easily seen in the ERTS imagery, along with many other apparently similar structures. The previously undetected

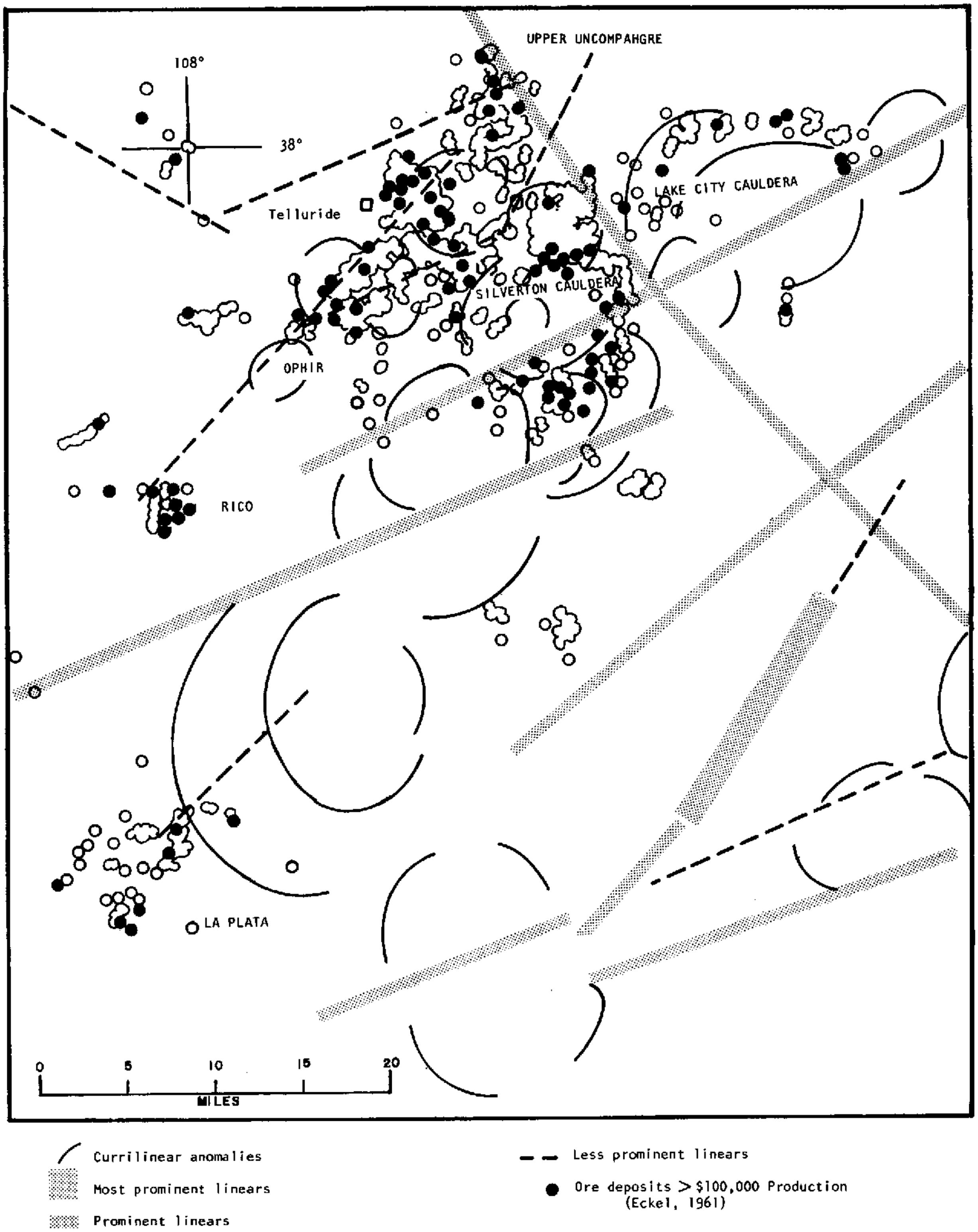

Figure 14. ERTS Data and Ore Deposits of the Western San Juan Mountains

caulderon northwest of the Silverton feature shows a close relationship to the deposits in the Telluride area. The Rico district, while not apparently related to any caulderon structure, does show an apparent relationship to a mapped linear. On the basis of these observations, it is concluded that ERTS data should prove very useful in helping to guide further exploration for concealed deposits in the San Juan volcanic field. This is further supported by the relationships of the Creede and Summitville deposits (Figure 11) with linears and curvilinear features. The Creede caulderon is known and a similar type feature has been reported previously for the Summitville area (Lipman and Steven, 1970). The San Luis caulderon reported north of Creede (Stevens, 1968) was not found by ERTS imagery on the initial interpretation, but a circular structure was detected there on close reexamination.

A comparison of the ERTS data with the reported mineralization in the Red River Area, New Mexico (near center bottom of Figure 11), shows a strikingly good correlation of the circular anomaly with the "Precambrian Gold Hill positive caldera block" (Carpenter, 1968). The northern-most northeast trending linear on Figure 11 coincides with the Red River fault and the Questa molybdenum mine (not shown in Figure 11) is located at the intersection of the Red River fault and the circular anomaly. Further, Carpenter shows a large number of precious and base metal prospects and mines scattered generally around the intersection of the two northeast striking linears and the circular anomaly. If this area is viewed in terms of a "simulated" remote reconnaissance prospect based on the ERTS data and the observed relationship between linears, curvilinear anomalies, and known mines in other areas, it is reasonable to predict success in an ensuing detailed exploration of the area.

b. *Uranium Deposits*

The uranium deposits of the Colorado region include vein-type deposits generally associated with the Colorado mineral belt (Walker et al., 1963) and the sandstone-type deposits of the Colorado Plateau region (Fischer, 1968). The vein deposits appear to be correlated with the ERTS data in essentially the same way as are the precious and base metal deposits. (See Subsection 2.a.)

The sandstone-type deposits are more scattered and do not show the relative close relationship to the linear and curvilinear features. Those in southwest Colorado appear to be loosely associated with the northwest trending lineaments, including the UNCOMPAHGRE FAULT, PARADOX, UTE and HENRY structures, as well as other nearby linears of varying strike as indicated in Figure 11. They also appear to be distributed around the laccolithic intrusive centers in the area including the La Sal Mountains and the Ute Mountains (Fischer, 1968).

It has been observed that the ores are generally associated with paleostream channels, and it has been hypothesized that they originated by soluble hexavalent uranium precipitating from ground waters or from telethermal solutions by being reduced to insoluble quadrivalent uranium compounds because of the presence of carbonaceous trash. It is suggested that the linears may serve as guides to locating paleostream channels on the basis that the same zones of weakness which influence today's drainage must have also influenced the paleodrainage in a similar manner. Thus, the linears should be useful as guides for reconnaissance prospecting in those covered areas back from the outcrops of the mineralized formations. This possibility should be investigated using 1:250,000 scale imagery and a more detailed interpretation than was possible during this study.

c. *Petroleum Occurrences*

Lineament control on the location of oil and gas fields is particularly striking in the San Juan basin (southwest portion of Area 2) where the known gas accumulations appear to be confined between the PARADOX and UTE lineaments and the oil field zone is bounded by the UTE and HENRY lineaments. In general, the basins are roughly outlined by lineaments or curvilinear anomalies, and the edges of some of the field appear to be defined by linears. The STEAMBOAT SPRINGS lineament has a series of five oil and two gas fields on it, or adjacent to it.

These and earlier observations in Area 3 (Saunders, et al., 1973) lead to the conclusion that ERTS lineament studies can be used to guide more detailed search methods in virgin areas. It is recommended, however, that these be performed using 1:250,000 scale imagery to obtain more detail than can be easily extracted at the 1:1,000,000 scale.

E. RESULTS IN OTHER AREAS TO DATE

1. Area 1 (Montanna Region)

The master mosaic was completed, the linears and curvilinear features were mapped, and the lineaments were defined. Data on the mines and petroleum occurrences have been mapped at 1:1,000,000 scale in preparation for interpretation.

2. Area 2 (New Mexico Region)

The master mosaic was reworked and reinterpreted following the preliminary work to take advantage of improved imagery coverage. The major lineaments were defined and their strikes were measured. Interpretation of the relationship of ERTS data to the economic deposits is nearly complete. Results were generally similar to those reported earlier (Saunders, Thomas, and Kinsman, 1973).

3. Area 4 (Northern Alaska) and Area 5 (Superior Province, Canada)

These mosaics were completed with only minor gaps in coverage. The linears and curvilinears were mapped, and the lineaments were defined. Data on the economic deposits are in the process of being mapped in preparation for detailed interpretation.

F. SEASONAL AND BAND STUDY

Representative scenes were chosen from each area, and all cloud-free coverage was laid out to compare for ease of interpretation of linears, tonal anomalies, and water features in terms of wavelength bands and seasons of coverage. This allowed a choice to be made of the best single bands and seasons for each type of feature. The results are summarized in Table 2.

In general, the combined use of bands 5 and 7 as separate images will provide adequate information for most interpretations of geologic features in all the areas studied, and the best seasons are in the spring and fall with moderate sun angles (40 to 50 degrees). The best single band and season varies, depending on the features being sought and the region to be studied.

TABLE 2. SUMMARY OF WAVELENGTH AND SEASONAL STUDY RESULTS

Region	Features Sought	Best Band	Best Time Of Year	Remarks
Montana	Linears	5 or 7	Fall	
	Tonals	5	Fall	
	Water	7	Fall	
Colorado	Linears	7	Winter	Band 5 fall coverage also good
	Tonals	5	Fall	
	Water	7	Fall	
New Mexico	Linears	5	Winter	Band 7 spring coverage also good
	Tonals	5	Spring or fall	
	Water	7	Spring or fall	
Canada	Linears	5	Spring	Band 7 in the summer also good
(Eastern)	Tonals	5	Summer	Band 7 early fall coverage also good
	Water	7	Summer	Band 5 in winter also good
	Roads and Trails	5	Summer	
Alaska	Linears	7	Late summer	Early winter also good
(Northern)	Tonals	7	Late summer	
	Water Features	7	Late summer	

The greater inherent information content of color composite products would indicate that these should be superior to single-band black and white images for geologic interpretation. The limited experience with the color products tends to bear this out, except for the difficulty in obtaining uniform hue and tonal qualities from print to print in large mosaics. This appears to be due to both processing difficulties and the necessity to mix seasonal coverages to obtain cloud-free images. When this problem is solved, the greater cost of the color products may be offset by the advantages of greater information content. However, at this time the single bands are easier to use and quite satisfactory for the purposes for which they are being used.

SECTION III

PLANS FOR REMAINDER OF PROGRAM

A. AREA 3 (NEW MEXICO REGION)

The lineament interpretation comparison with the economic deposits of the region is nearly complete, and this will be included in the final report in essentially the same format and depth of analysis as Area 2 was presented in this report. This analysis will include some minor revision of the preliminary results which are attributed to a greatly improved mosaic and a complete reinterpretation of the linears and curvilinear anomalies.

B. AREAS 1, 4, AND 5 (MONTANA REGION, SUPERIOR PROVINCE, CANADA AND NORTHERN ALASKA)

Data for all these areas are currently in the process of being drafted and combined as overlays for final interpretation. This work will be completed and will be compared with economic deposits. The results will be presented, essentially, as Area 2 was presented in this report.

C. FINAL REPORT

The final report will be prepared during October and November 1973 as a comprehensive presentation of all results from this study.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

Preliminary conclusions and recommendations are included in the preceding text, including the Preface.

SECTION V
NEW TECHNOLOGY

No new technology has been developed under this contract.

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